AP® Chemistry: From Shells to Subshells Class Activity[[1]](#footnote-2)

**Question: Do all electrons in the same level have the same energy?**

From the Shells Activity, one important conclusion we reached based on the first ionization energy experimental data is that electrons in higher shells require less energy to remove. We have experimental data that indicates energy required to remove an electron depending on the shell the electron occupies. (In which shell does an electron require more energy to remove: the second shell or the fourth shell?) An interesting question we could ask (one that cannot be answered from the experimental data of the first ionization energy) is: Do all electrons in the same shell require the same amount of energy to remove? We can answer this question if we look at photoelectron spectroscopy (PES) data for the atoms.

In a photoelectron spectroscopy experiment, any electron can be ionized when the atom is excited. Like the first ionization, only one electron is removed from the atom; however, in the PES experiment it can be any electron, not just the electron that requires the least amount of energy.

Additional examples of photoelectron spectra data are available at

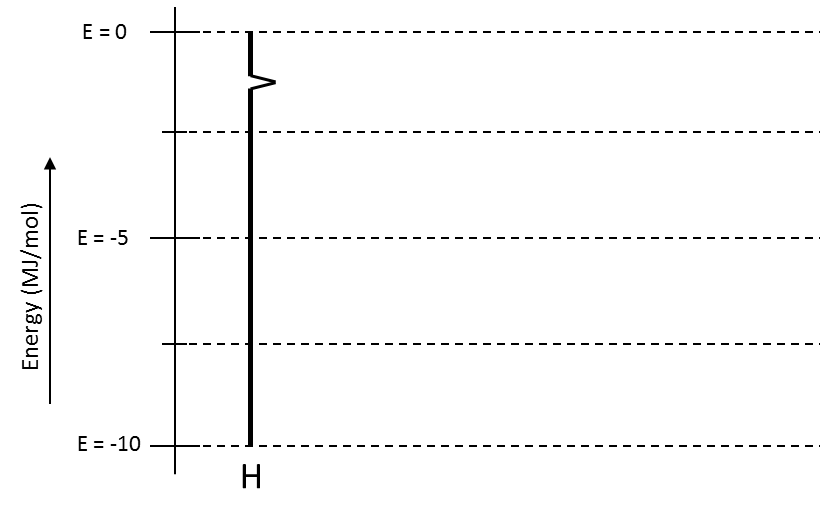
* <http://www.chem.arizona.edu/chemt/Flash/photoelectron.html>   
  To display the spectrum, click on the element in the periodic table.
* Spencer, James N., George M. Bodner, and Lyman H. Rickard. *Chemistry: Structure and Dynamics,* 5th Edition. [Hoboken, NJ]: Wiley and Sons, 2012.
* <http://www.cbc.arizona.edu/rss/pes/tutorials/tutorials.htm>

It is recommended that you have the pre-class Shells Activity for reference while working on this activity.

Prior to completing this activity, your teacher will show you a model for how Photoelectron Spectroscopy (PES) uses a radiation source and an electron energy detection source to determine the energy of electrons that are ejected from an atom. The spectra that appear in this activity are idealized to make them easier to interpret.

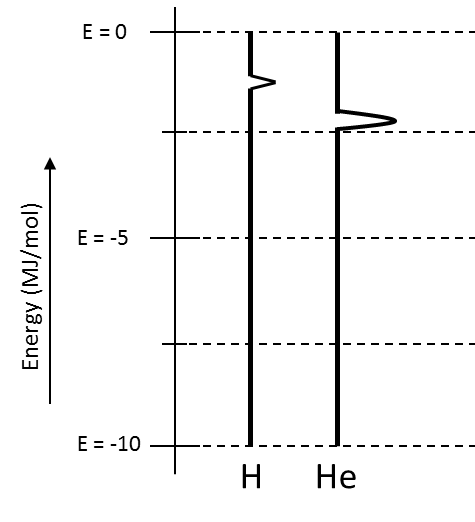
Look at the PES spectrum for hydrogen shown in Figure 1 below.

1. The label on the y-axis is energy, with the units megajoules per mole (MJ/mol). What is depicted on the x-axis below?



**Figure 1**

1. How does the photoelectron spectrum for the hydrogen atom given in Figure 1 relate to the first ionization energy for hydrogen?
2. Helium is next, but before looking at the photoelectron spectrum, answer the following:
   1. how many electrons does helium have in its first shell?
   2. Refer back to the Shells Activity and obtain the first ionization energy for a helium atom.
   3. Using Figure 1, sketch what the PES plot would look like if
      1. the same amount of energy is required to remove each of the electrons in the Helium atom.
      2. different amounts of energy are required to remove each electron.
3. Look at the PES plot in Figure 2 and compare it to your prediction from the previous question. Describe what you see and the conclusions you can reach. Be sure to comment about the relative energy of the peaks and the number of electrons for each peak for both elements.

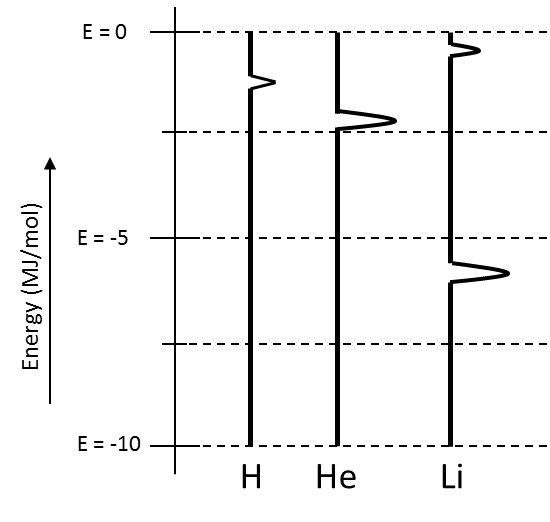
**Figure 2**

1. The next element is lithium.
   1. How many electrons does lithium have, and what shells do those electrons occupy?
   2. Before looking at the PES for lithium, predict what you believe the spectrum would look like.

Note: you do not have to predict the exact energies for each electron, but you should make reasonable estimates based on the first ionization energy for lithium and the PES for helium. Use the data for lithium from the Shell Activity to help make your predictions.

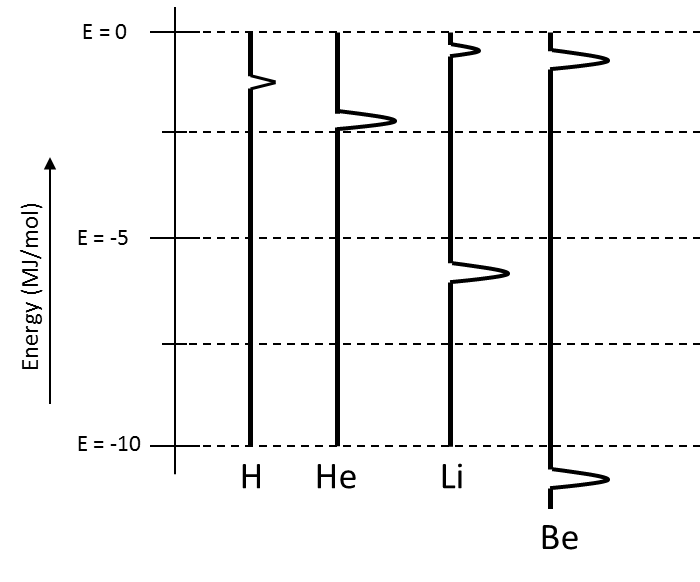
* 1. Sketch your best estimate of what the PES plot would look like for lithium on Figure 2.

1. Examine the PES plot in Figure 3 and compare it to your prediction from the previous question.
   1. Label each peak in Figure 3 with the shell occupied by the electrons that correspond to that peak.
   2. Describe what you see and the conclusions you can reach. Be sure to comment about the relative energy of the peaks and the number of electrons indicated by each peak in the lithium spectrum.



**Figure 3**

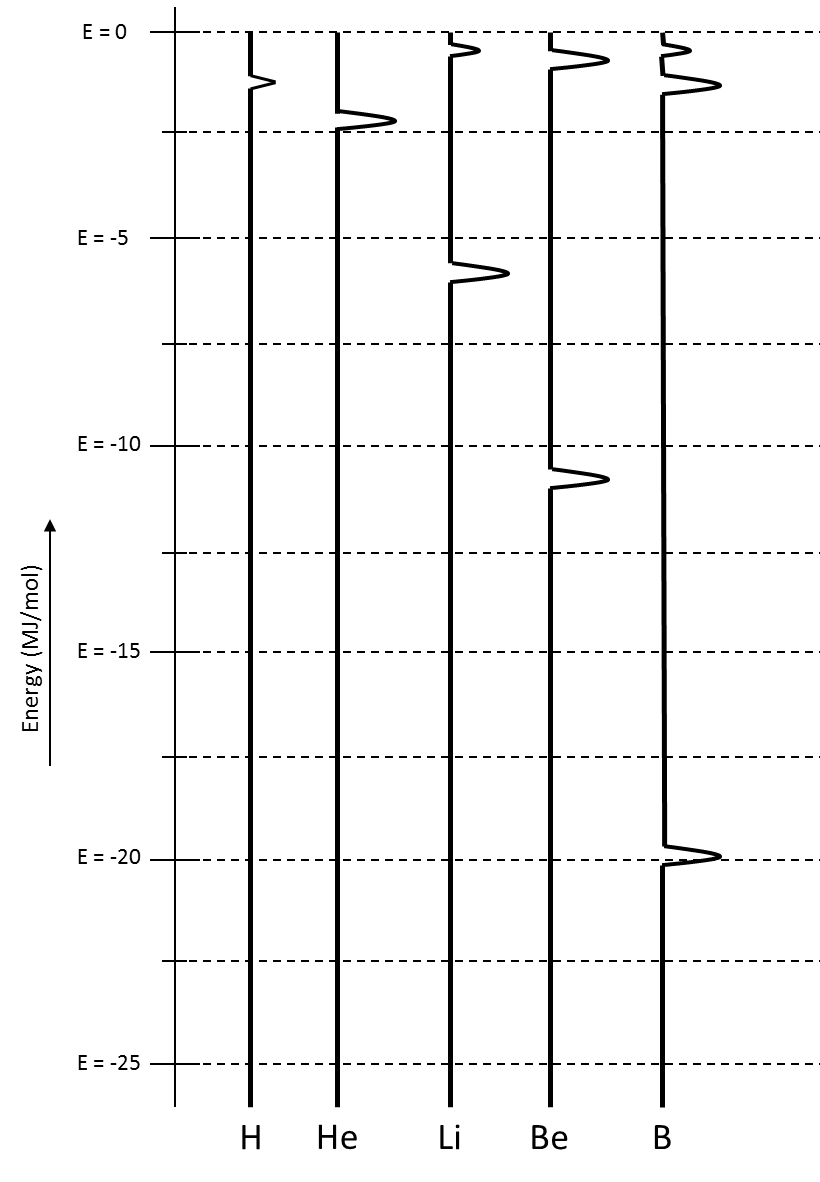
1. The next element is beryllium.
   1. How many electrons does beryllium have, and what shells do those electrons occupy?
   2. For the spectrum for beryllium, predict
      1. how many peaks:
      2. the number of electrons for each peak:
      3. the approximate relative energies of each peak (hint: think about how many protons beryllium has compared to lithium, and if that will make it easier or harder to remove the electrons)
   3. Using Figure 3, sketch what you anticipate the spectrum of beryllium will look like.
2. Examine Figure 4 below.
   1. Label each peak in Figure 4 with the shell occupied by the electrons that correspond to that peak.
   2. Based on the number of protons in the nucleus, why are the peaks for beryllium lower on the plot than for lithium?



**Figure 4**

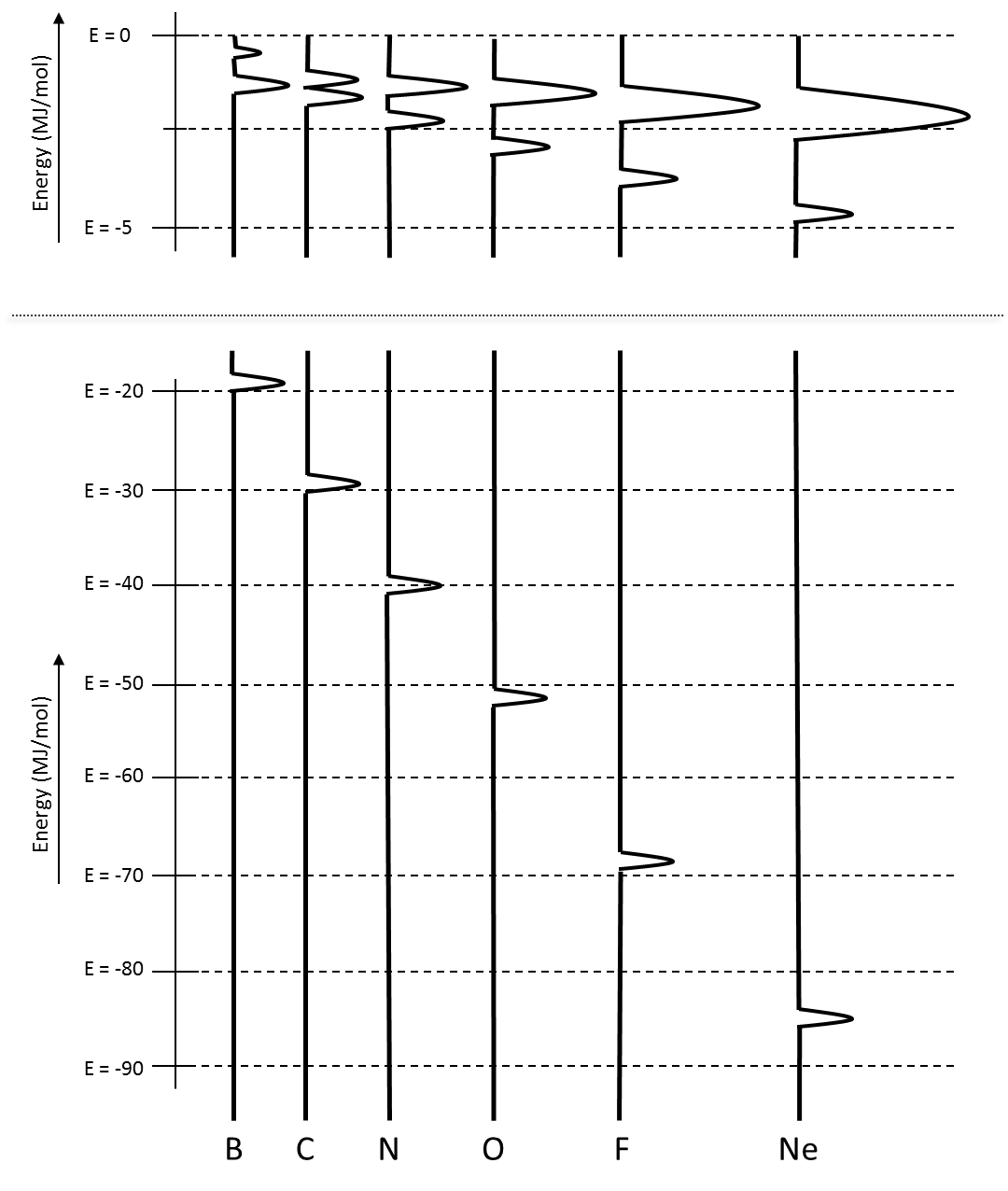
1. The next element is boron.
   1. How many electrons does boron have, and what shells do those electrons occupy?
   2. For the spectrum for boron, predict
      1. how many peaks:
      2. the number of electrons for each peak:
      3. the approximate relative energies of each peak (hint: think about how many protons boron has compared to beryllium and lithium, and if that will make it easier or harder to remove the electrons)
   3. Using Figure 4, sketch what you anticipate the spectrum of boron will look like
2. Examine Figure 5 below.
   1. How can there be three peaks?

* 1. Label each peak in the spectrum for boron in Figure 5 below.



**Figure 5**

Since the energy gap between energy levels is getting very large, we will start splitting the spectra from this point forward to make them easier to fit on one page. Examine the data in Figure 6 for the spectra of several elements from Period 2 of the periodic table, and then answer the questions on the next page. You might find it helpful to label which shell is represented by each peak.



**Figure 6**

1. Answer the following questions based on the PES plots for hydrogen through neon.
   1. After examining the spectra, a student concludes, “The electrons in the second shell all have the same energy.” Would you agree or disagree with this statement? Explain.
   2. How many “subshells” are found in the second shell? \_\_\_\_\_\_\_ The first shell? \_\_\_\_\_\_\_
   3. Moving systematically through the second period, from lithium to neon:
      1. How many electrons are in the first shell for each element in Period 2? \_\_\_\_\_\_\_
      2. What happens to the energy required to remove an electron in the first shell moving from left to right in the second period? Support your observation with an explanation that references the relevant subatomic particles.
      3. What happens to the energy of the electrons in the outermost shell as you look at the data for elements across Period 2?
2. Examine the simulated spectra for elements in the third period at the following website - <http://www.chem.arizona.edu/chemt/Flash/photoelectron.html>. Click on the element’s icon on the periodic table to view the PES spectrum. You will note that energy is on the x-axis here.
   1. Are there any surprises in the data?
   2. Briefly summarize your observations, and provide an explanation based on subatomic particles, energy shells, and subshells.
3. A notation has been agreed upon for writing an electron configuration to identify the location of the shell and subshell of each electron in an atom. Shells are labeled with a number (1, 2, 3, etc.), and subshells are labeled with letters (*s*, *p*, *d*, and *f*). Every shell contains an *s* subshell. Use this information to write a complete electron configuration for the first 10 elements (atomic numbers 1-10) of the Periodic Table
4. Look at the PES plots for potassium, calcium, and scandium.
   1. Something very interesting happens in the spectrum for scandium that we have not seen for any element prior to scandium. Explain.
   2. If one electron is removed from scandium, which electron requires the least amount of energy to remove? (identify the shell and subshell)

1. This activity has been adapted from a draft generated by John Gelder of Oklahoma State University. I have altered some of the questions and presented the data slightly differently than the original. The original version of this activity can be found in the AP® Chemistry Teacher Community resources section. [↑](#footnote-ref-2)